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Status Update and Results from the U.S. Department of Energy Regional Carbon Sequestration Partnership Initiative

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Abstract

A major component of the U.S. DOE Carbon Storage Program is Infrastructure, which includes the seven Regional Carbon Sequestration Partnerships (RCSPs). The RCSP Initiative began in 2003 with an assessment of the CO_2 storage resource in various geologic formations throughout the seven partnerships, and has subsequently focused on small- and large-scale field projects. RCSP field projects involve site-specific characterization and application of simulation and risk assessment, and monitoring, verification, accounting (MVA) and assessment technologies in different types of storage reservoirs in various geologic depositional environments and different geographic regions. Field testing has validated multiple technologies and tested new tools and approaches, and shown the need for integration of multiple tools for monitoring. Results of the field projects have improved our understanding of CO_2 injection, fluid flow and pressure migration, and geomechanical and geochemical impacts of injection, and are providing experience and knowledge of operation at scale which is essential for broad, commercial deployment of storage technologies.

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Keywords: U.S. DOE Carbon Storage Program; National Energy Technology Laboratory; carbon capture and storage (CCS); Regional Carbon Sequestration Partnerships (RCSPs); monitoring, verification, accounting (MVA) and assessment; CO_2 injection; site-specific characterization; simulation and risk assessment

1. Introduction

The Carbon Storage Program being implemented by the U.S. Department of Energy's (DOE) Office of Fossil Energy (FE) and managed by the National Energy Technology Laboratory (NETL) is focused on developing and advancing technologies, both onshore and offshore, that will significantly improve the effectiveness of carbon capture and storage (CCS), reduce the cost of implementation, and be ready for widespread commercial deployment

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in the 2025–2035 timeframe.

A major component of the Carbon Storage Program is Infrastructure, which includes the seven Regional Carbon Sequestration Partnerships (RCSPs), site characterization projects, and other small- and large-scale field projects. The majority of the effort is conducted by the RCSP network to help develop the technology and infrastructure, to implement large-scale carbon dioxide (CO_2) storage regionally, and provide the foundation for commercial-scale CO_2 storage.

The RCSP Initiative began in 2003 with initial characterization to assess CO_2 storage potential in various geologic formations throughout the seven partnerships. In 2005, validation of the most promising regional storage opportunities was initiated through a series of small-scale field projects. Currently, the RCSPs are conducting large-scale field projects involving the injection of up to 1 million metric tons of CO_2 per project, and in some cases exceeding 1 million metric tons. RCSP field projects involve site-specific characterization and application of simulation and risk assessment, and monitoring, verification, accounting (MVA) and assessment technologies in different types of storage reservoirs in various geologic depositional environments and different geographic regions. They aim to improve our understanding of CO_2 injection, fluid flow and pressure migration, and geomechanical and geochemical impacts from CO_2 injection, as well as develop and validate a “commercial toolbox” of technologies for cost-effective, safe, and permanent storage in all types of storage reservoirs. Finally, they aim to communicate lessons learned from field projects to industry, regulators, and the public through Best Practice Manuals [1]. Progress toward achieving these goals will be summarized in this paper.

2. Overview

In 2003, DOE created a network of seven RCSPs to help develop the technology and infrastructure needed to implement large-scale CO_2 storage in different regions and geologic formations. The RCSPs are public/private partnerships comprising more than 400 organizations over 43 states and four Canadian provinces (Figure 1). The RCSPs include representatives from state and local agencies, regional universities, national laboratories, non-government organizations, foreign government agencies, engineering and research firms, electric utilities, oil and gas companies, and other industrial partners.

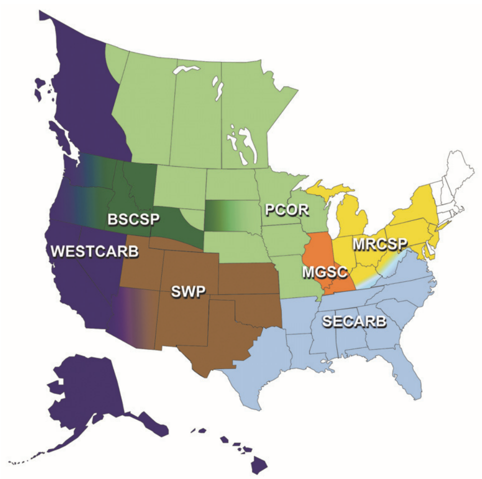


Fig. 1. Map of the Regional Carbon Sequestration Partnership regions.

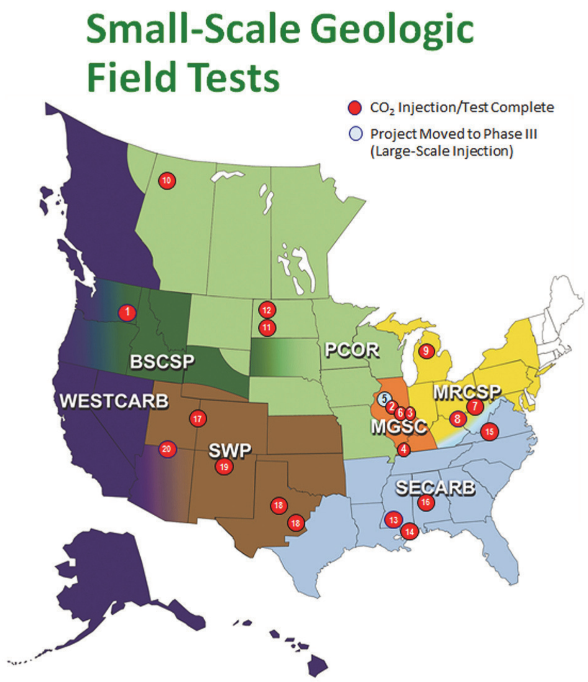
One of the early, important, accomplishments of the RCSPs was the documentation of large stationary CO_2 sources and estimates of CO_2 storage resource within their regions. This information has been published in a series of periodically updated *Atlases* [2]. *Atlas IV,* published in late 2012, documents the location of 4,245 large, stationary CO_2 sources (each emitting more than 100,000 metric tons per year) with total annual emissions of approximately 3,279 million metric tons of CO_2. While not all saline formations in the United States have been examined by the RCSPs to date, *Atlas IV* reports an estimated CO_2 storage resource ranging from approximately 2,100 billion metric tons to more than 20,000 billion metric tons in saline formations. Similarly, *Atlas IV* reports approximately 226 billion metric tons of CO_2 storage resource in mature oil and gas reservoirs and approximately 56 to 114 billion metric tons of potential CO_2 storage resource in unmineable coal seams.

The CO_2 prospective storage resource estimate is defined as the fraction of pore volume of porous and permeable sedimentary rocks available for CO_2 storage and accessible to injected CO_2 via drilled and completed wellbores. A consistent methodology for calculating storage resource has been developed by NETL and members of the seven RCSPs [3] and applied consistently across all regions. The methodology is based on volumetric methods for estimating subsurface volumes, in-situ fluid distributions, and fluid displacement processes. Oil and gas reservoirs are assessed at the field level, while saline formations and unmineable coal areas are assessed at the basin level. For saline formations, the storage resource is calculated using eq. (1):

$$M = A * h * \varphi_{tot} * \rho * E_{saline} \tag{1}$$

where M = mass of CO_2, A = total area of the basin, h = gross formation height, φ_{tot} = total bulk volume of available pore space, ρ = density of CO_2 at storage conditions, and E_{saline} = efficiency factor. The efficiency factor, first introduced in *Atlas I*, represents a fraction of the total pore space that is filled by CO_2, and reflects the effect of different factors, such as buoyancy and reservoir heterogeneity, that inhibit CO_2 from contacting 100 percent of the pore volume.

Since 2005, the majority of effort in the RCSP Initiative has been directed toward small- and large-scale field projects. During the Validation Phase (also referred to as Phase II) of the RCSP Initiative, 19 small-scale field projects, collectively involving injection and monitoring of more than 1.0 million metric tons of CO_2, were successfully completed. Eight were carried out in depleted oil and gas fields, five in unmineable coal seams, five in clastic and carbonate saline formations and one in basalt. Eleven different classes of geologic storage formations (deltaic, shelf clastic, shelf carbonate, strandplain, reef, lacustrine, eolian, fluvial and alluvial, turbidite, coal, and basalt) have been identified based on depositional environment [4], and the small-scale projects were carried out in eight of these formations. Figure 2 summarizes project location and geologic information for the small-scale projects. The projects provided information on reservoir and seal properties of regionally significant formations, testing and initial validation of modeling and monitoring technologies. The projects also helped establish familiarity with CO_2 storage technologies among many stakeholder groups. Detailed information on the projects can be found on the NETL website [5].



RCSP	Formation Type	Reservoir Class
BIG SKY	SALINE 1	Basalt
MGSC Midwest Geological Sequestration Consortium	OIL-BEARING 2 3 4 SALINE 5 COAL SEAM 6	Deltaic, Shelf Clastic, Fluvial, Coal
MRCSP Midwest Regional Carbon Sequestration Partnership	SALINE 7 8 9	Shelf Carbonate, Strandplain, Shelf Clastic
PCOR Plains CO_2 Reduction Partnership	OIL-BEARING 10 11 COAL SEAM 12	Shelf Carbonate, Reef, Coal
SECARB Southeast Regional Carbon Sequestration Partnership	OIL-BEARING 13 SALINE 14 COAL SEAM 15 16	Fluvial, Deltaic, Coal
SWP Southwest Regional Partnership on Carbon Sequestration	OIL-BEARING 17 18 COAL SEAM 19	Reef, Shelf Carbonate, Coal
WESTCARB West Coast Regional Carbon Sequestration Partnership	SALINE 20	Shelf Carbonate

Fig. 2. Map showing location and characteristics for the RCSP small-scale field projects.

Sharing knowledge obtained in the R&D projects sponsored by the DOE Carbon Storage Program is essential for the deployment of CCS. The lessons learned from the RCSPs' small-scale projects have been integrated into a series of Best Practice Manuals (BPMs). The first editions of the BPMs were completed in 2011 and will be updated regularly to include new lessons learned from large-scale projects.

Results of the Validation Phase Projects provided a basis and a foundation for the RCSP large-scale, Development Phase (also referred to as Phase III) field projects. Injection is underway in six projects with more than 7.0 million metric tons safely injected as of September 2014. There are three saline formation injections, three involving enhanced oil recovery (EOR) and one combined saline/EOR test, representing four different depositional environments. Figure 3 summarizes project location and geologic information for the large-scale projects.

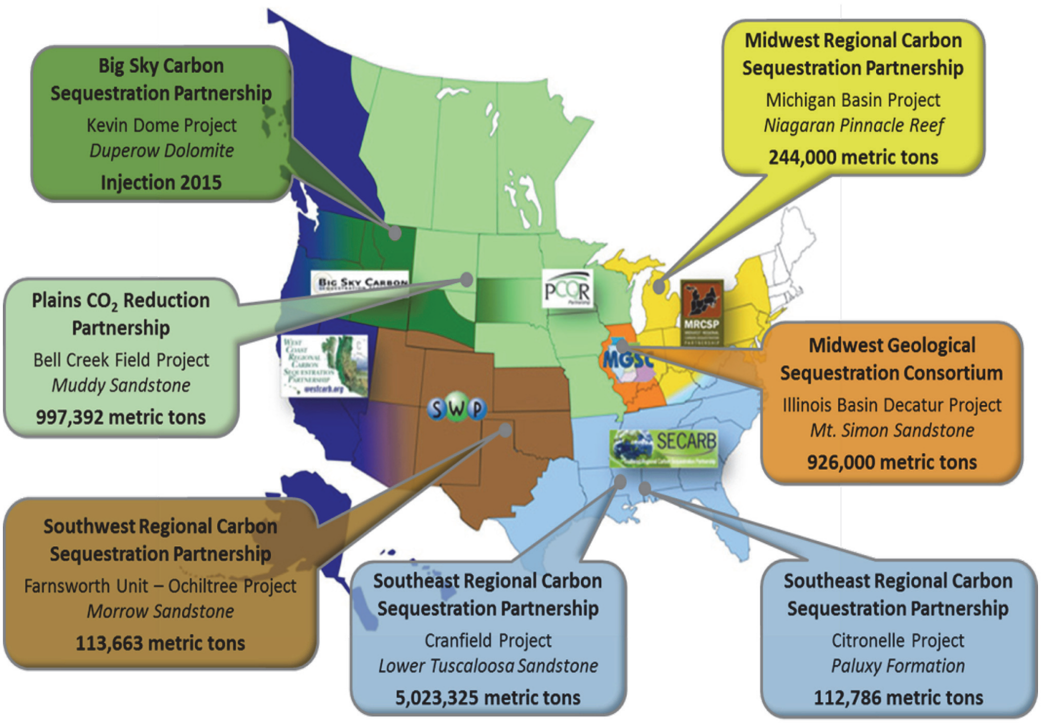


Fig. 3. Map showing location and injection volumes for the RCSP large-scale projects as of September 2014.

3. Modeling and Simulation

The RCSPs have employed a variety of numerical simulation tools to support design of the tests, predict plume movement and pressure changes, and assess geomechanical and geochemical impacts of injection. Table 1 is a partial list of the diverse simulation codes, including commercial as well as research codes, which have been applied by the RCSPs. The list reflects the fact that there is no single all-purpose code. Code choice varies according to the type of storage reservoir (i.e., saline, depleted oil/gas, or coal), user preference and familiarity, as well as the number and type of processes incorporated (i.e., hydrologic, thermal, chemical, or mechanical), and the degree of coupling among these processes.

Table 1. Partial list of the diverse simulation codes used for the large-scale field projects

Code Name	MGSC	MRCSP	PCOR	SECARB	SWP	Big Sky
CO2-PENS					X	X
CO2-PROPHET		X	X			
COMSOL			X	X		
CORE2D				X		
ECLIPSE/ECLIPSE300	X				X	X
Fekete		X				
FLAC			X			X
GEM		X	X	X	X	
Geochemist's Workbench	X				X	
IMEX		X				
IPARS				X		
MODFLOW	X	X		X		
Petra		X				
PetraSeis		X				
Petrel	X		X		X	X
PHREEQC			X	X		
STOMP		X			X	
T2Well (ECO2H w/drift flux model)						
Techlog			X		X	
TOUGH2	X		X	X		X
TOUGH2 and SEAWAT (linked)	X					
TOUGHREACT				X	X	X
WellTest		X				
WinProp			X			
Velo					X	
VISAGE	X					

3.1. Geologic Modeling

All of the RCSPs are developing models to predict the movement of the CO_2 in the reservoir as well as the pressure front in response to injection operations. The starting point for the reservoir model is a geologic model of the subsurface, which is developed based on existing geologic and geophysical data as well as new data from dedicated characterization wells. Using technologies developed for hydrocarbon exploration and production, the geologic models are built using software platforms (e.g., Petrel) which enable integration, visualization and analysis of multiple data types, including well logs, core and seismic data.

Porosity and permeability data, derived from well logs and laboratory measurements on core, are being analyzed using various geostatistical techniques to populate grid cells in the static geologic model with appropriate site-specific reservoir properties. Figure 4 shows the interpreted porosity distribution in one of the reservoir layers in the geologic model for the SWP Farnsworth Unit- Ochiltree Field large-scale project. This project involves injection of CO_2 into a depleted oil field in which existing wells provide considerable amounts of data. Logs from 181 wells were used in generating the model of over 700,000 grid cells, each with dimensions of approximately 30 m by 30 m.

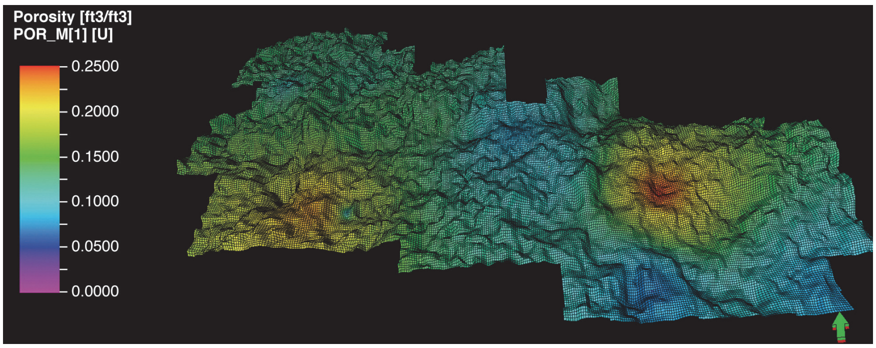


Fig. 4. Interpreted porosity distribution in one of the reservoir layers in the geologic model for the SWP Farnsworth Unit, Ochiltree Field project.

The SECARB Citronelle project is injecting into the Paluxy saline formation which overlies oil reservoirs, so a large number of existing wells are present (400+ in the Citronelle field), but, in this case, most of the legacy wells do not have porosity logs. Three new wells with modern porosity logs were drilled on well pads with existing abandoned wells and these paired wells were used to train a neural network to predict porosity using existing self potential (SP) and resistivity logs [6].

All RCSPs have made extensive use of seismic data, both surface 3-D and vertical seismic profiling (VSP), in developing their geologic models. Seismic data provides information on subsurface structures such as faulting, as well as lithostratigraphic unit boundaries. In most conventional 3-D seismic surveys, the P-wave (compressional wave) is the primary source of information. The Big Sky Kevin Dome project is utilizing 9-component 3-D seismic, which involves acquisition and interpretation of shear waves in addition to P-waves. Well data suggests that the target Duperow dolomite is fractured, and shear wave data can help characterize the orientation and density of fractures, which could influence movement of the CO_2 in the reservoir.

Since seismic wave velocity is affected by porosity, 3-D seismic data can be inverted using various methods to estimate porosity throughout the 3-D volume of the geologic model. These are particularly useful and important techniques when there are few wells, as is likely the case for many saline formation storage projects. Figure 5 is cross-sectional view of the results of seismic inversion of 3-D data for porosity in the Mt. Simon formation, which is the reservoir target of the MGSC Illinois Basin – Decatur Project (IBDP). It shows both high and low porosity which is quite continuous laterally, but variable in the vertical direction, which could influence the flow of the CO_2 in the reservoir.

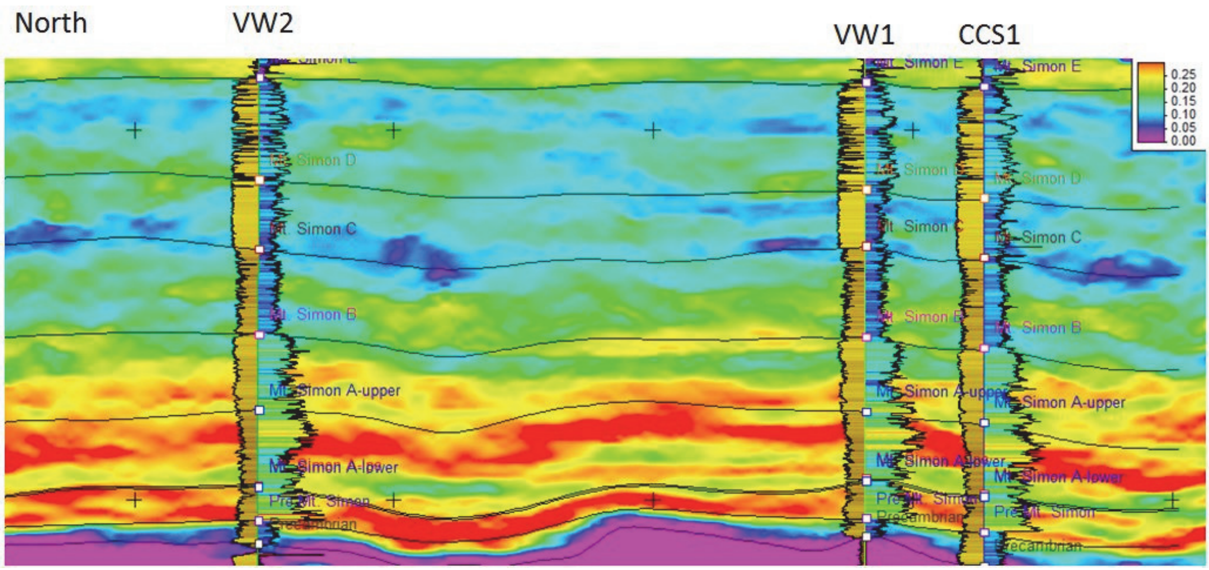


Fig. 5. Cross-sectional view of the results of seismic inversion of 3-D data for porosity in the Mt. Simon formation, which is the reservoir target of the MGSC IBDP.

MRCSP was able to match the processed results of the higher resolution VSP to the interpreted static earth model of the Niagaran pinnacle reef, as can be seen in Figure 6. The processed VSP data showed a distinct increase in frequency content and more character of reef structure compared to the surface 3-D seismic results, which are hampered by the thick glacial till at the surface and high-angle geologic features of the reef. Future work on the VSP data involves relating the internal structures to the lithostratigraphic unit boundaries developed within the static earth model.

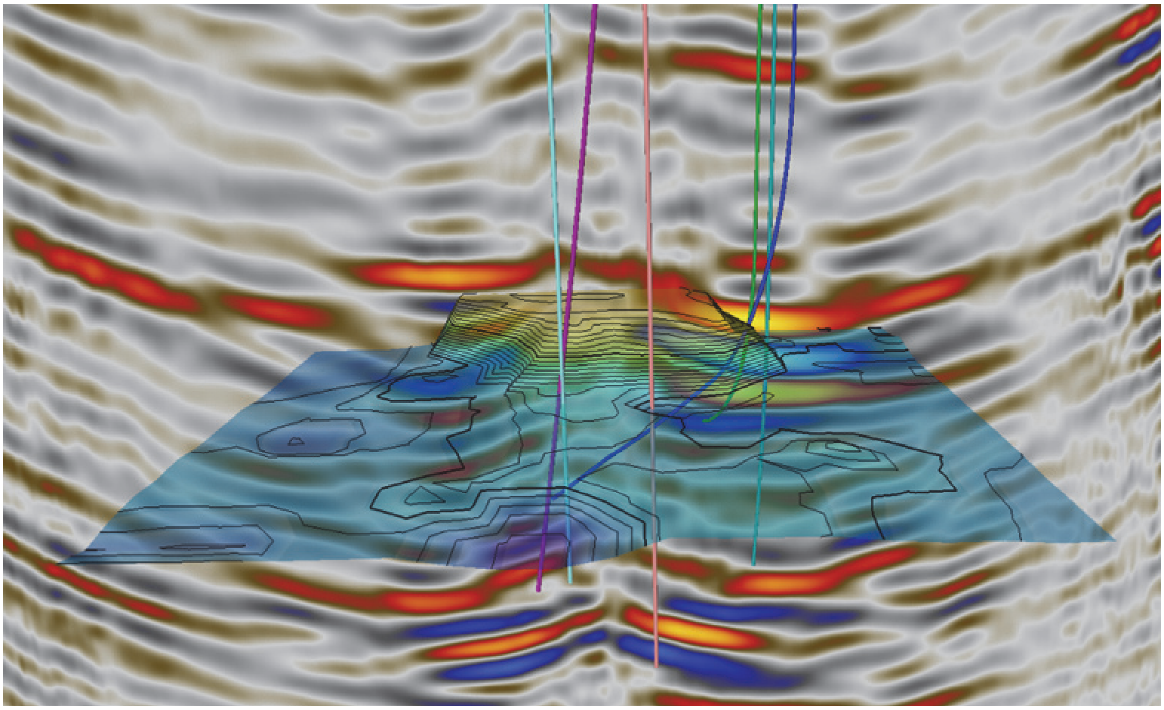


Fig. 6. East-west transect shown within the final static earth model; surface shown is the A-2 carbonate, which matches well with the bright reflector on the section.

3.2. Reservoir Simulation and Process Modeling

Reservoir simulation is the foundation in each of the RCSP large-scale projects because it provides predictions of the temporal and areal distribution of the CO_2 and pressure, which can then be used to develop a comprehensive monitoring plan and later compared with monitoring data. In projects involving injection into depleted oil reservoirs, it is necessary to first simulate the historic hydrocarbon production and injection activities. Figure 7 shows results for reservoir simulation of the PCOR Bell Creek field project in which associated CO_2 storage is taking place in conjunction with active EOR operations. Historic production, injection, water cut rates, and pressure were matched (Figure 7a and 7b), followed by prediction of the CO_2 injection. Figure 7d is a forward model illustrating one realization of injected and stored CO_2 versus time. The difference in the injected and stored CO_2 curves is due to the production of CO_2 and subsequent reinjection. All of the purchased CO_2 is expected to be stored at the end of the project, and is the subject of the monitoring program.

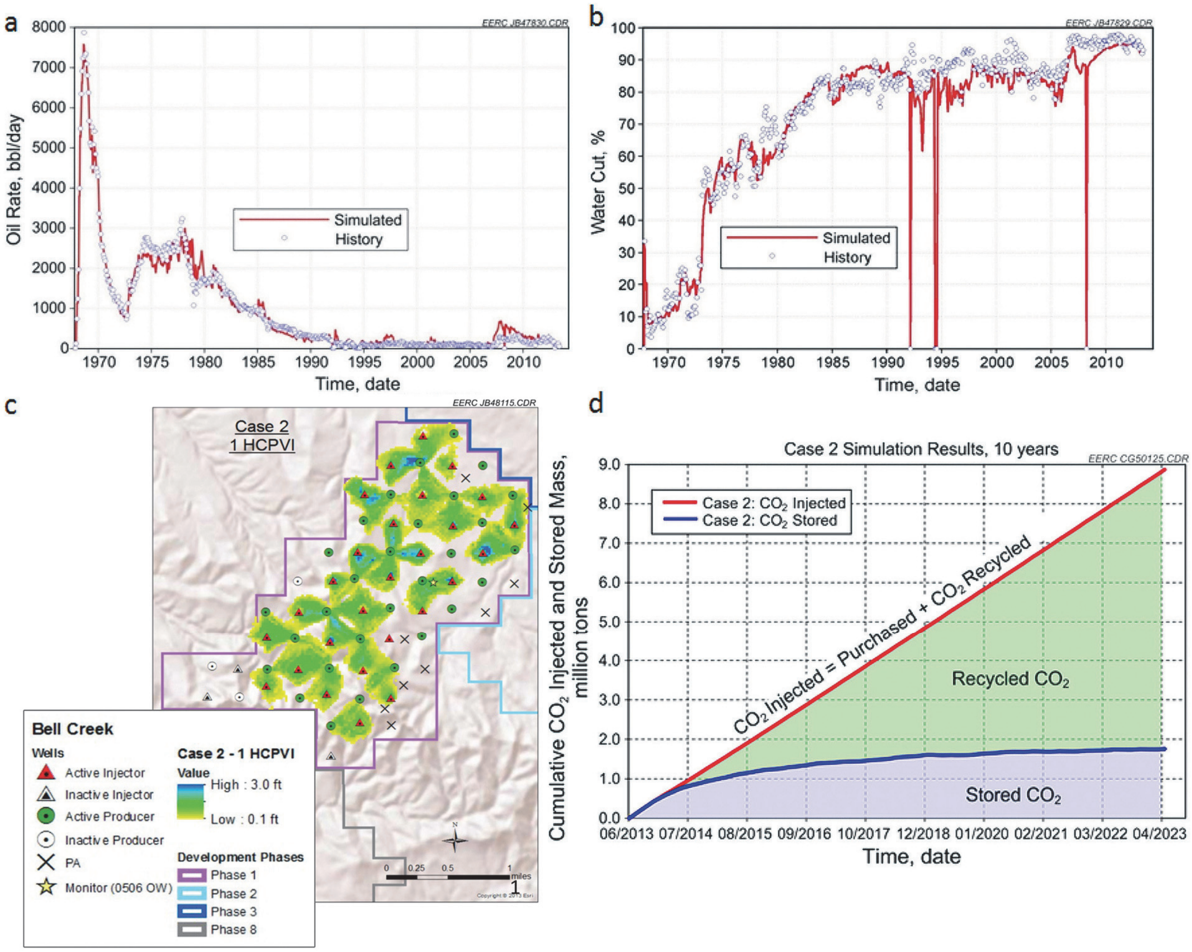


Fig. 7. Reservoir simulation results for the PCOR Bell Creek field project: (a) and (b) History match of oil production rate and water cut; (c) Prediction of the CO_2 plumes after 1 HCPVI; (d) Prediction of stored and injected CO_2 versus time for one prediction case. The difference in the injected and stored CO_2 curves is due to recycling of CO_2. All of the purchased CO_2 is expected to be stored at the end of the project.

Once monitoring data becomes available, numerical simulation of reservoir processes becomes an integral part of data analysis. In the SECARB Cranfield project, intensive monitoring was carried out in the Detailed Area Study (DAS), in which there was one injection and two observation wells at a depth of >3000 m with spacing <80 m. Monitoring data included well-test data, reservoir saturation tool (RST) measurements, pressure and temperature data both in and above the injection zone, and samples of bottom-hole fluids. Hosseini et al. performed reservoir simulation using a stochastic approach to generate multiple, equally likely realizations to try to match all the field data [6]. The authors found that an important factor affecting pressure response and plume extent is relative-permeability curves - for example, end-point saturations directly affect plume size. They also confirmed that methane exsolution from brine due to CO_2 injection was a factor affecting plume size and plume arrival times.

Monitoring at the DAS also included sensitive pressure measurements in an overlying permeable zone (referred to as Above Zone Monitoring Interval, AZMI) separated from the underlying CO_2 injection reservoir by a confining layer. Geomechanical modeling showed that a small fluid pressure increase in the AZMI was possible without any hydraulic connection between the AZMI and injection reservoir, due to the mechanical deformation of the rock caused by CO_2 injection.

4. MVA Approaches and Tools

In order to support development and deployment of a commercial toolbox for monitoring, a broad portfolio of MVA techniques is being applied in the large-scale projects. Each of the projects employs a combination of atmospheric, near-surface, and subsurface methods, though the selection of specific techniques is tailored to the individual site conditions and research objectives of the project. Figure 8 presents a summary of the monitoring plan for the MGSC IBDP.

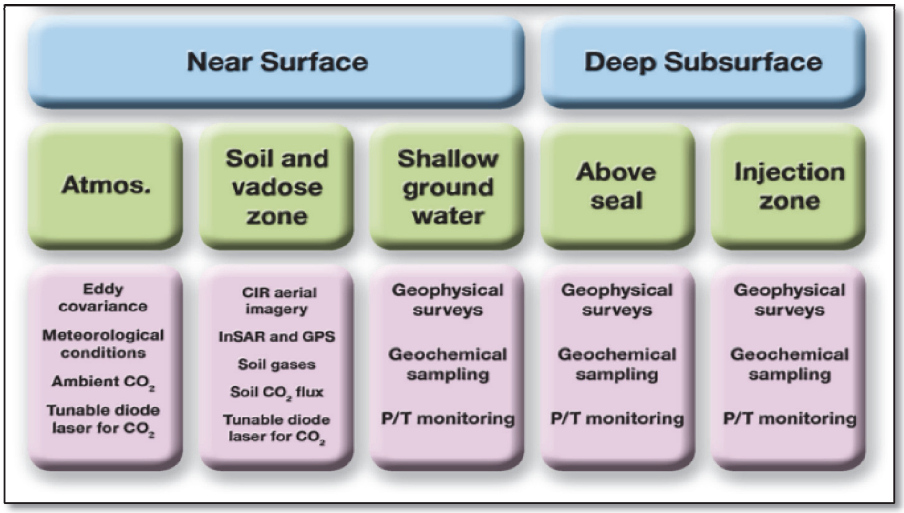


Fig. 8. Elements of the monitoring plan for the MGSC IBDP.

4.1. Subsurface Monitoring

Seismic technology is generally considered to be an important potential tool for monitoring the CO_2 plume in the reservoir. The general approach is to use seismic methods in the time-lapse mode, which means that survey results from before and after injection are compared to find differences in seismic response that can be attributed to the presence of CO_2 in the reservoir. Time-lapse seismic surveys have been completed in two of the RCSP large-scale projects. In the MGSC IBDP, two pre-injection, 3-D VSPs were performed and to date three time-lapse repeats were performed after about 74,000, 433,000, and 730,000 metric tons had been injected. Time-lapse effects of the injected CO_2 were seen in NRMS (Normalized Root Mean Square) repeatability metric, which showed an increase in magnitude and areal extent over time. It was concluded that the time-lapse, 3-D VSP data gives a sense of the areal extent of the bulk of the CO_2 plume, though thin or low CO_2 saturation stringers were not imaged. Differences in ground surface conditions between surveys added noise and complexity to analyses.

It was also observed that further constraint could be put on the vertical extent of the plume through integration with time-lapse well logging and pressure data, illustrating the general importance of integration of multiple types of data for monitoring.

In the SECARB Cranfield project, time-lapse crosswell seismic and 3-D surface seismic data were collected. Time-lapse crosswell tomography was conducted between each pair of DAS wells. Tomograms showed strongly heterogeneous distribution of CO_2 between the two observation wells, which are 30 m apart.

Time-lapse surface seismic surveys were recorded at pre-(2007) and post-(2010) injection stages to monitor the subsurface fluid plume. The injection interval, appearing as a thin layer in the well-log data, presented a challenge for imaging using conventional methods. Application of a basis pursuit inversion (BPI) method resulted in improved resolution of the inverted acoustic impedance image, providing a good fit to well log data and good correlation between time lapse changes in acoustic impedance and the location of injection wells [7]. Figure 9a shows time-lapse seismic results and Figure 9b overlays results of reservoir simulation.

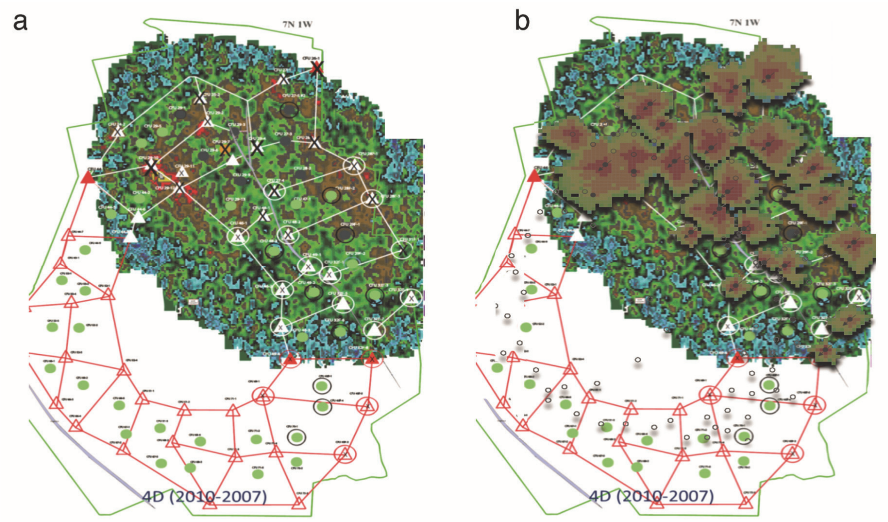


Fig. 9. (a) Time-lapse seismic results [red-brown areas represent largest time-lapse change]; (b) Results of reservoir simulation [red-brown areas are high gas saturation] overlain on seismic results for SECARB Cranfield project.

In the MGSC IBDP, permanent installation of downhole geophone arrays has enabled acquisition of high quality microseismic data. To date, moment magnitudes range from -2.14 to 1.14. Analysis of the measurements continues, but the data shows that the microseismic events form distinct spatial clusters, distributed between the Lower Mt. Simon Sandstone, the Pre-Mt. Simon Unit and the Precambrian basement (CO_2 is injected into the Lower Mt. Simon). The data tend to show a slight decline in moment magnitudes.

All RCSP large-scale projects have included subsurface fluid pressure measurement as an integral part of their monitoring program. Pressure is used as a control parameter for injection operations. Monitoring and analysis of pressures provides information on reservoir structure, properties, and boundary conditions, plume movement in the reservoir, and the effectiveness of wellbore seals and geologic confining units. As discussed in a previous section, pressure is a key parameter in reservoir history matching. The MRCSP Michigan Basin large-scale injection project has carried out extensive history matching of the pressure build-up and fall-off associated with injection testing in the late-stage pinnacle reef. The approach was to simulate the pressure response in the injection well and monitoring wells using the injection records for each CO_2 injection test. Results showed that the reef behaves as a closed hydrologic system, with permeability that ranges between approximately 1 to 40 mD.

In the MGSC IBDP, pressure measurements helped to confirm the presence of flow baffles in the reservoir which were not evident in the seismic data. In the SECARB Cranfield project, AZMI pressure monitoring was validated as a method for monitoring out of zone fluid movement.

A number of other advanced subsurface monitoring methods are being evaluated, validated, and utilized in the RCSP large-scale tests. In the SECARB Cranfield project, crosswell, continuous, electrical resistivity tomography (ERT) was successfully undertaken between the two observation wells in the DAS, showing time-lapse changes in resistivity linked to saturation changes in the reservoir. Also at the DAS, fast and rate-dependent breakthrough and transport of natural and introduced tracers confirmed preferential flow though fluvial channel geometries, which affects sweep efficiency and storage capacity. The MGSC IBDP monitoring system included a first-in-the-world deep (2,200+ m) deployment of an eleven-level pressure and fluid sampling tool.

Saline formation storage will likely involve relatively fewer wells than storage associated with mature oil and natural gas operations, which motivates development of technologies to maximize data from a single well. In the SECARB Citronelle project, a Modular Borehole Monitoring (MBM) system was deployed, which included an 18 level tubing deployed clamping geophone array (at approximately 1,828 to 2088 m depth), two in-zone quartz pressure/temperature gauges, a "U-tube" for high frequency in zone fluid sampling, a heating cable and fiber optic sensing cable [8]. The cabling was molded into an innovative "flat pack" which reduced run-in time and cost (Figure 10). Fiber optic sensing components, which offer the potential benefits of long-life operation in harsh environments and high spatial resolution, are also innovative. The fiber optic cable in the MBM system enabled distributed temperature sensing, and incorporation of a heater provided the added capability of heat pulse monitoring, which can be used for detecting small amounts of fluid movement behind casing. At the SECARB Citronelle project, the fiber optic cable was also used for one of the first-ever in-situ tests of distributed acoustic sensing for seismic monitoring [9,10].

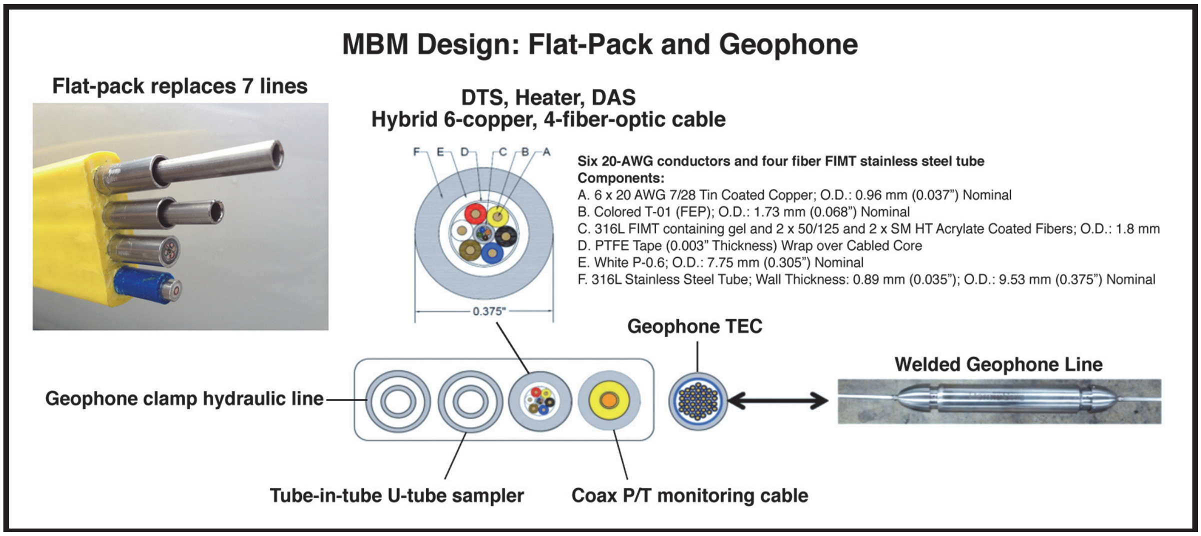


Fig. 10. MBM design for the SECARB Citronelle project showing flat-pack and components.

4.2. Surface and Near-surface Monitoring

The RCSP large-scale projects have incorporated extensive monitoring in the near-subsurface and at the surface, providing assurance that no injected CO_2 has been released. Monitoring techniques included:

- Soil gas sampling: CO_2 concentrations, $N_2/O_2/CO_2/CH_4$ ratios, stable isotopes, noble gases, introduced tracers (perfluorocarbons) and volatile organic compounds (VOCs)
- Groundwater sampling: CO_2 concentrations, alkalinity, pH, major ions, metals, dissolved inorganic and organic carbon, dissolved gases, total dissolved solids, organics, inorganics, hydrocarbons, isotopes and noble gases
- IRGA (infrared gas analyzer) for atmospheric CO_2 concentrations and eddy covariance for CO_2 atmospheric flux measurements
- Accumulation chamber for surface CO_2 soil flux measurements
- Land surface deformation monitoring using Interferometric Synthetic Aperture Radar (InSAR) analysis

Many surface and near-surface monitoring approaches require that a baseline be established so that natural variations in a measurement parameter can be distinguished from a potential release of injected CO_2. In the MGSC IBDP it was found that variations in key shallow (30 to 60 m) groundwater chemical parameters (calcium, magnesium, and potassium) require a year or more of baseline monitoring to assess natural variations that are related to annual climatic variability in rainfall and temperature.

A process-based approach for surface and near-surface monitoring, which would reduce the need for pre-injection background measurements, was tested for the first time in the SECARB Cranfield project. This approach uses simple gas ratios (e.g., CO_2, CH_4, N_2, O_2) to discern between in-situ-generated gases and exogenous gases in the vadose zone [11].

The large footprint of potential commercial storage projects presents a challenge for cost-effective surface detection of potential releases. The MGSC IBDP and Big Sky Kevin Dome project are testing new laser-based tools for measurement of atmospheric CO_2 concentrations. Airborne hyperspectral imaging to look for anomalous plant stress is also being tested at the Kevin Dome project. MRCSP is investigating the applicability of InSAR in Northern

Michigan, which is mostly covered by agricultural areas and forests, to look for any quantifiable, small-scale, surface-level changes related to injection of CO_2.

5. Risk Assessment

Risk management, which incorporates risk assessment, has been integrated into the planning, monitoring, and overall operation of all of the RCSP large-scale projects. The two main objectives of risk management are to make sure that important risks are identified, and to make sure that all identified risks are reduced to and/or held to acceptable levels. The details of risk management approaches differ from project to project, but most of the RCSP large-scale projects employ an iterative approach utilizing an expert panel-based risk assessment process. The expert panel meets to develop a risk registry of potential risks, consequence severity, and likelihood of occurrence. Potential risks include financial, operational, and management risks as well as technical risks. Following the risk assessment, the project team develops and implements risk mitigation actions. After some period of time, the risk assessment process is repeated to ensure the effectiveness of the risk mitigation actions. Figure 11 is an example of the format of a risk registry.

	CONSEQUENCE				LIKELIHOOD				
					A: Remote	B: Unlikely	C: Possible	D: Probable	A: Certain
	Health and safety (HS) And Environmental protection (E)	Cost	Reputation	Schedule to start-up of operations	Very unlikely (P<0.05) to occur during life of project	Unlikely to occur during life of project	50/50 chance of occurring during life of project	Likely to occur during life of project	Very likely (P>0.95) to occur during life of project
CONSEQUENCE SEVERITY E: Persistent Severe	HS: On site & off site exposures/injuries. E: Persistent severe damage, Extensive remediation required. Environment restored > 5 years.	More than $10 million	National or International media attention. Regulators shut down operations.	More than 12 months	M	M	H	H	H
D: Severe	HS: On site injuries/exposures leading to absence from work more than 5 days or long term negative health effects. E: Severe environmental damage. Remediation measures required. Environment restored < 5 years	$1 to $10 million	Regional media attention. Regulatory or legal action taken	6-12 months	L	M	M	H	H
C: Moderate	HS: Lost time event/on site injury leading to absence from work up to 5 days, or affecting daily life activities more than five days. E: Damage managed by Company response teams, env. restored < 2 years.	$100 to $1000 k	Local media attention. Regulatory or legal action likely	3-6 months	L	L	M	M	H
B: Minor	HS: Minor injury or health effect - affecting work performance, such as restricting work activities, or affecting daily life activities for up to 5 days. E: Damage, but no lasting effect	$10 to $100 k	Public awareness may exist, but there is no public concern	1-3 months	L	L	L	M	M
A: Slight	HS: Slight injury or health effect - not affecting work performance or daily life activities. E: Damage contained within premises.	Less than $10 k	On-site communications	Less than 1 month	L	L	L	L	M

Fig. 11. Example project risk registry matrix (L – low risk, M – medium risk, H – high risk). Colors are indicative of risk level. Risk scenarios in the green band are considered acceptable, those in the red band are currently unacceptable and must be reduced, and risks in the yellow band are of concern but may be tolerable without further risk reduction

6. Operational Experience

All RCSP large-scale projects are providing important real-world operational experience in operation and monitoring of storage projects. Two projects are noteworthy in providing operational experience of fully integrated capture and storage projects. The MGSC IBDP is a fully integrated industrial source and storage project in which the source is the Archer Daniels Midland Company (ADM) ethanol plant. The CO_2 is 99+ percent pure and is a byproduct of the fermentation of corn to produce the ethanol. Dense phase CO_2 is delivered to the injection well via a 6-inch diameter pipeline supplied by two four-stage reciprocating compressors with an integrated glycol dehydration system. A unique aspect of the project is the development and implementation of a real time monitoring and operational control system which integrated the process control of the ethanol plant's compression-dehydration system with the injection and monitoring system for storage [12].

The CO_2 for the SECARB Citronelle project is obtained from a demonstration-scale, post-combustion CO_2 capture facility at Southern Company's subsidiary Alabama Power's existing 2,657 MW Barry Electric Generating Plant in Mobile County, Alabama. The Citronelle project is an integral component of a plan by Southern Company, and its subsidiary, Alabama Power, to demonstrate integrated CO_2 capture, transport and storage technology for an existing pulverized coal-fired power plant. A small amount of flue gas from Plant Barry (equivalent to the amount produced when generating 25 MW of electricity) is being diverted from the plant's #5 coal burning unit and captured using a process developed by Mitsubishi Heavy Industries (MHI) to produce high purity CO_2. The captured CO_2 is compressed at Plant Barry and transported approximately 20 km by a dedicated 4-inch pipeline to the injection location at Citronelle Field. Variation in the volume of flue gas processed by the capture system, occurring over a time frame of a few hours, results in variable CO_2 rates, pressures and temperatures which need to be accommodate by the transport and injection system. Active management of the pipeline's pressure, volume and temperature (PVT) conditions was required to maintain CO_2 in the supercritical state in the pipeline under these variable conditions. At the injection site a variable-speed injection pump was installed to appropriately handle the range in CO_2 injection volumes.

7. Raising Public Awareness of CCS

Through the field projects, as well as other activities, the RCSPs have made significant contributions to raising public awareness of CCS in the U.S. Impactful activities include:

- Active engagement of multiple stakeholder groups, including academia, environmental groups, and hundreds of industry participants
- RCSPs have worked closely with state geologic surveys
- RCSPs actively participate in the Outreach Working Group (OWG)
- RCSPs have worked closely with local, state, and Federal regulators, providing extensive data in support of USEPA Underground Injection Control (UIC) permits and permitting experience which will support future CCS projects
- Partnership researchers have provided many briefings for officials and policymakers at regional, state, and local levels
- RCSPs have participated in CCS regional training centers
- Knowledge sharing through Atlases and online resources, expert assistance in helping to prepare BPMs

Experience from the Validation Phase small-scale projects showed that identification of local community concerns and implementation of strategies to address these concerns is integral to project implementation. To aid in public outreach, the RCSPs have developed many types of region-specific products on geology and projects, including:

- General information about climate change and CCS
- Detailed information on geologic storage potential
- General information on the partnerships and its participants
- Technical reports
- Detailed information about field tests
- Information and educational products of many kinds
- Links to other resources with additional information

8. Summary and Conclusions

Since 2003 the RCSP Initiative has made major contributions to advancing geologic storage technologies toward commercialization in the United States. A consistent methodology for calculating storage resource in saline formations, depleted oil and gas reservoirs, and unmineable coal, has been developed and applied consistently across all regions. During the Validation Phase of the RCSP Initiative, 19 small-scale field projects were successfully completed in diverse types of storage reservoirs in eight different depositional environments. Currently, in the Development Phase of the RCSP Initiative, injection is underway in six large-scale projects. RCSP field projects involve site-specific characterization and application of simulation and risk assessment, and MVA technologies in different types of storage reservoirs in various geologic depositional environments and different geographic regions. Multiple technologies have been validated in the field projects, and new tools and approaches have been tested. Seismic technology has been used extensively in site characterization and has been successfully used for monitoring. Results of the field projects show, however, that integration of multiple types of data are key for characterization and monitoring. Another key finding from field projects is the importance of determining deposition-related heterogeneity and site-specific conditions on behavior of the CO_2 in the reservoir, and performance of MVA methods. Overall, results of the field projects have improved our understanding of CO_2 injection, fluid flow and pressure migration, and geomechanical and geochemical impacts of injection, and are providing experience and knowledge of operation at scale which is essential for broad, commercial deployment of storage technologies.

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